Letters to the Editor

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Angular Distributions of Protons from the Reaction $O^{16}(d,p)O^{17}$

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October 30, 1950

THE reaction $O^{16}(d, p)O^{17}$ gives a number of groups of protons, of which the two corresponding to the ground state and first excited state of O^{17} have Q-values of 1.925 Mev and 1.049 Mev (Buechner *et al.*[1]). The intensities of these two groups have been measured at seven angles by Heydenburg and Inglis,[2] using deuteron energies between 0.65 Mev and 3.05 Mev.

We have used the 8-Mev deuteron beam from the University of Liverpool cyclotron, and a scattering camera in which photographic plates record particles emitted from a gas target at all angles from 10° to 165°, to obtain detailed angular distributions for the charged particles emitted in a number of deuteron-induced reactions. A full account of the method and results will be published elsewhere, but because of their theoretical interest (Butler[3]), the angular distributions of the two groups of protons from the reaction $O^{16}(d, p)O^{17}$ are presented here.

Tracks of protons from the two groups were identified by their ranges in the photographic emulsion, and the number of protons in each group, found in a given area, was determined for a series of angles from 10° to 160°. Ordinarily, measurements were made at 5° intervals, but at the more critical angles the interval was reduced to 2.5° or even to 1.25°. Using these numbers and the geometry of the apparatus, we calculated the angular distributions of the two proton groups in the center-of-mass system. These are shown in Fig. 1, in which the ordinates are proportional to the cross sections per unit solid angle in the center-of-mass system, at a center-of-mass angle ϕ, and the abscissae are $\cos\phi$.

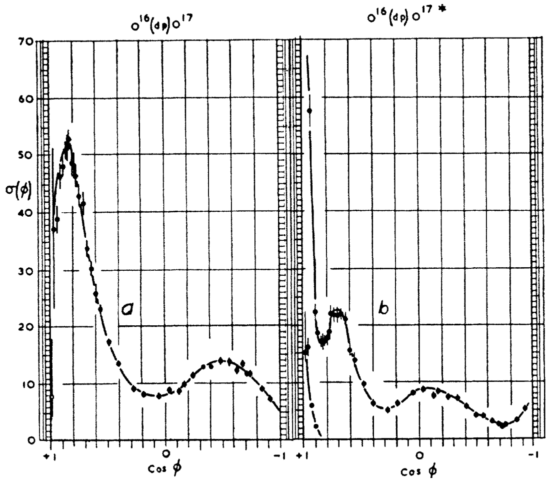

FIG. 1. $O^{16}(d, p)O^{17}$ angular distributions in the center-of-mass (c.m.) system: ϕ = c.m. angle, $\sigma(\phi)$ = c.m. differential cross section in arbitrary units. Curve a is for formation of O^{17} in the ground state, and curve b is for the 0.88-Mev excited state.

Figure 1a shows that when the O^{17} nucleus is formed in its ground state, there is a definite maximum in the intensity at $\cos\phi=0.83$ ($\phi=34°$). At higher angles, the intensity falls to a minimum at about 85°, rises to a smaller maximum at 120°, and falls again towards 180°. Below 34° the intensity falls, apparently tending to zero in the forward direction, although it is not excluded that it may rise again at very small angles; it is hoped that further experiments will show the behavior at angles too small to be studied with this apparatus.

In contrast to this, the intensity of protons from the formation of O^{17} in its excited state at 0.88 Mev (Fig. 1b) has a peak at $\cos\phi=0.7$ ($\phi=45°$) and a minimum at $\cos\phi=0.84$ ($\phi=33°$), rising steeply as the angle decreases from 33°.

The most interesting feature of these results is the difference in behavior of the two groups at angles below 50°. Butler[3] has shown that a stripping process, in which no compound nucleus is formed, can give one of several characteristic angular distributions, according to the spins and parities of the reacting nuclei. The observed results for small angles fit very well with the theoretical predictions, and it appears that (d, n) and (d, p) angular distributions may be of use in determining the spins and parities of ground and excited states in many nuclei.

[1] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).
[2] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).
[3] S. T. Butler, Phys. Rev. **80**, 1095 (1950). Following letter.

On Angular Distributions from (d, p) and (d, n) Nuclear Reactions

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October 30, 1950

THE purpose of this note is to report the results of calculations which show how information regarding the spins and parities of nuclear energy levels can be obtained from angular distributions from nuclear reactions of the type $X(d, p/n)Y$ without the necessity of assuming properties of resonance levels of a compound nucleus. This work was commenced, at the suggestion of Professor Peierls, when experimental angular distributions for certain (d, p) reactions[1] were made available to him some time ago by Professor Rotblat. All exhibited a pronounced structure at small angles, and the work of Holt and Young[2] gives similar results. Such a structure must arise from contributions from high incident angular momenta of classical impact parameters larger than the nuclear radius. The obvious conclusion is that the reactions proceed, at least in part, by a stripping process in which one of the particles of the deuteron is absorbed into the nucleus, while the other merely carries off the balance of energy and momentum. Such a process is possible in the case of (d, p) and (d, n) reactions because of the low binding energy and large diameter of the deuteron.

I have calculated angular distributions resulting from such a stripping process by equating, at the nuclear surface, the exact wave function for a particle outside the nucleus to the interior wave function. After some simplification the resulting boundary equations can be solved in such a way that unknown properties of the nuclear wave functions affect the important parts of the distributions merely as a constant multiplying factor. The resulting curves show a pronounced maximum near the forward direction, the position of which is determined in each case by the spins and parities of the nuclear states involved. This is due to the fact that the requirements of conservation of angular momentum and of parity allow the nucleus to accept a particle (say a neutron) with only very limited values of angular momenta l_n, and the angular distribution depends very sensitively on these

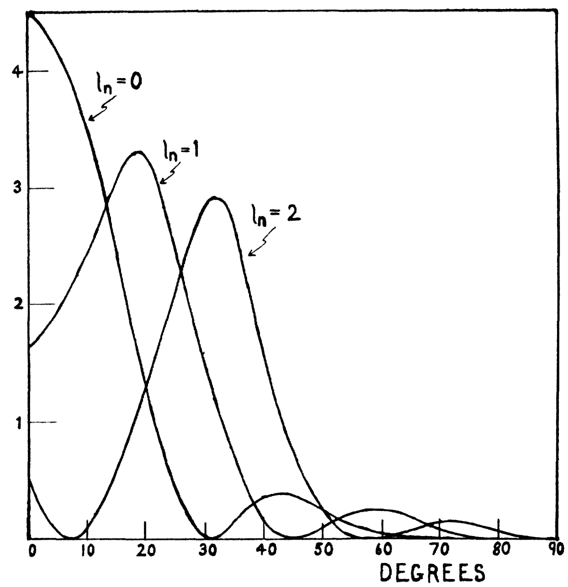

FIG. 1. Theoretical angular distributions for (d, p) and (d, n) reactions for different angular momentum transfers to the initial nucleus.

values. For deuteron energies above the Coulomb barrier, the distributions for the different values 0, 1, and 2 of l_n are generally of the form shown[3] in Fig. 1.

The possibility that the whole deuteron may enter the nucleus has been neglected. This is justified for large impact parameters, and hence the results should be reliable at small angles which are important for the present analysis. It is found that in any one case the experimental distribution agrees extremely well at small angles with one of the possible theoretical curves. We can thus identify the angular momentum transferred to the nucleus, and hence determine the spin and parity of the final nucleus from that of the initial nucleus.

For example, from the experimental angular distributions[1] for the reaction $O^{16}(d, p)O^{17}$ with 7.9-Mev incident deuterons, it is found that the theoretical curve required to obtain coincidence with the experimental one at small angles is, for the ground state of O^{17} that for $l_n=2$, and for the first excited state (0.88 Mev above ground) that for $l_n=0$. This agreement is illustrated in Figs. 2 and 3. Since the ground state of O^{16} has spin 0 and even parity, this implies that the ground state of O^{17} has spin 5/2 or 3/2

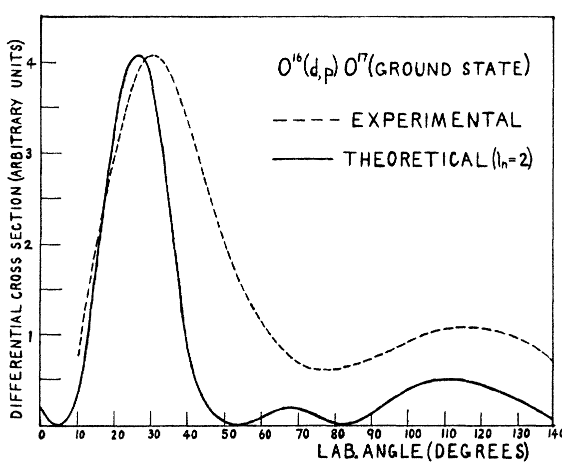

FIG. 2. Comparison of experimental and theoretical distributions for the ground-state transition of the reaction $O^{16}(d, p)O^{17}$ with 7.9-Mev incident euterons. The theoretical curve is that for $l_n=2$.

and even parity, and that the first excited state of O^{17} has spin 1/2 and even parity.

Table I gives spin and parity assignments which have so far been made from the experimental evidence of Burrows, Gibson,

TABLE I. Spin and parity assignments.

Reaction	Ground state initial nucleus	Final nucleus Ground state	First excited state
$O^{16}(d, p)O^{17}$ [a]	0+	(5/2 or 3/2)+	1/2+
$N^{14}(d, p)N^{15}$ [a]	1+	(1/2, 3/2, or 5/2)−	
$C^{12}(d, p)C^{13}$ [a]	0+	(1/2 or 3/2)−	
$Al^{27}(d, p)Al^{28}$ [b]	5/2+	(2 or 3)+	(0, 1, 4, or 5)+

[a] See reference 1.
[b] See reference 2.

and Rotblat, and of Holt and Young. For the ground states of C^{13} and N^{15} the assignments are consistent with what is already known.

Full details of these calculations, together with further assignments of spins and parities, will be published elsewhere.

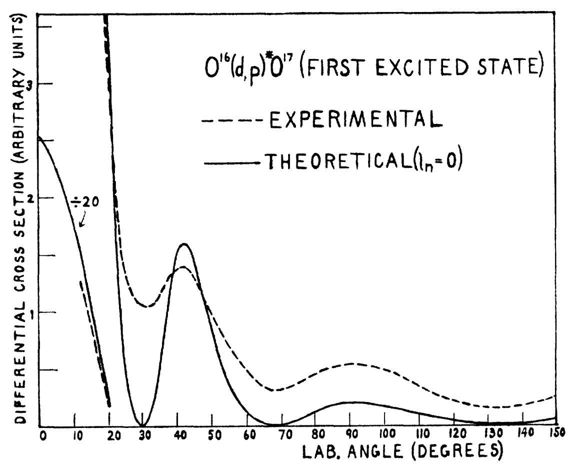

FIG. 3. Comparison of experimental and theoretical distributions for the transition to the 0.88-Mev excited state of O^{17} in the reaction $O^{16}(d, p)O^{17}$ with 7.9-Mev incident deuterons. The theoretical curve is that for $l_n=0$.

My sincere thanks are due to Professor Peierls not only for suggesting the problem, but also for many very helpful discussions during the course of the work. I must also thank Professor Rotblat and Dr. Gibson for making experimental results available before publication.

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[1] Burrows, Gibson, and Rotblat, Phys. Rev. **80**, 1095 (1950), preceding letter, and report at Harwell Nuclear Physics Conference, 1950.
[2] Holt and Young, Proc. Phys. Soc. London **78**, 833 (1950).

[3] Although not shown in Fig. 1, the absolute values of the maxima usually decrease with increase of l_n, so that in those cases in which more than one value of l_n is allowed, the lowest value is the most important.

On the Entry into the Earth's Atmosphere of 57-Kev Protons during Auroral Activity

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October 27, 1950

THE occurrence of a major auroral storm during the two nights of August 18 and 19, 1950, made it possible to utilize a grating spectrograph of sufficient resolution to study the Hα wave-length region. The spectrograph was pointed toward the magnetic zenith for three spectra and toward the north magnetic horizon for five spectra. Some spectra from both orientations